

# A new nucleon resonance in $\eta$ photoproduction

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## Abstract

We present in this talk recent investigations on the nucleon-like resonance  $N^*(1675)$  newly found in  $\eta$  photoproduction by the GRAAL, Tohoku LNS- $\gamma$  and CB-ELSA collaborations. We focus on the production mechanism of the  $N^*(1675)$ , examining its spin and parity theoretically within the framework of the effective Lagrangian method. We explicitly consider  $D_{13}(1520)$ ,  $S_{11}(1535)$ ,  $S_{11}(1650)$ ,  $D_{15}(1675)$ ,  $P_{11}(1710)$ ,  $P_{13}(1720)$  as well as possible background contributions. We calculate the differential cross sections and beam asymmetries for the neutron and proton targets. It turns out that there is manifest isospin asymmetry in  $\eta$  photoproduction, which can be explained by the asymmetry in the transition magnetic moments:  $\mu_{\gamma pp^*} \ll \mu_{\gamma nn^*}$ . Moreover, we find that the spin-1/2 state is preferred and this observation implies that the new resonance may be identified as a non-strangeness member of the baryon antidecuplet.

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## I. INTRODUCTION

Recently, the GRAAL collaboration has reported a new nucleon resonance  $N^*(1675)$  from  $\eta$  photoproduction [1, 2], which has a narrow decay width:  $\Gamma_{N^* \rightarrow \eta N} \simeq 40$  MeV. The Fermi-motion corrections being taken into account, the width may become even narrower:  $\sim 10$  MeV [3]. This narrow width is a typical feature for the pentaquark exotic baryons [4, 5, 6]. Moreover, the production process of the  $N^*(1675)$  largely depends on its isospin state of the target nucleons: A larger  $N^*(1675)$  peak is observed for the neutron target, while it is suppressed for the proton one, i.e.  $\mu_{\gamma nn^*} \gg \mu_{\gamma pp^*}$ . Interestingly,  $N^*(1675)$  being assumed as a member of the baryon antidecuplet ( $\overline{10}$ ), this large isospin asymmetry can be well explained in the chiral quark-soliton model ( $\chi$ QSM) [7, 8]. In fact, the strong isospin asymmetry is an exact consequence of  $U$ -spin conservation in the flavor  $SU(3)$  limit [9]. Concerning the spin and parity, their assignments are not yet determined unambiguously. Although the  $\eta$ -MAID has assumed  $J^P = 1/2^+$  as suggested by the  $\chi$ QSM [3], in our previous work [10], we have shown that  $J^P = 1/2^-$  is equally possible in comparison with the experimental data. In the present work, we want to investigate the  $\eta$  photoproduction, including the following six nucleon resonances,  $D_{13}(1520)$ ,  $S_{11}(1535)$ ,  $S_{11}(1650)$ ,  $D_{15}(1675)$ ,  $P_{11}(1710)$  and  $P_{13}(1720)$ , in a fully relativistic manner. We ignore the contributions from  $N^*(1680)$  and  $N^*(1700)$  considered in Ref. [3], since their branching ratios to  $\eta N$  channel are negligible. The nucleon-pole terms and vector-meson exchanges are also taken into account as backgrounds. In order to test the spin and parity of the new resonance, we investigate four different cases:  $J^P = 1/2^\pm, 3/2^\pm$ . As a result, we observe that  $\mu_{\gamma nn^*(1675)} = 0.1 \sim 0.2$  and  $\mu_{\gamma pp^*(1675)} \simeq 0$  for  $J^P = 1/2^\pm$  whereas  $\mu_{\gamma nn^*(1675)} = 0.01 \sim 0.02$  and  $\mu_{\gamma pp^*(1675)} \simeq 0$  for  $J^P = 3/2^\pm$  to reproduce the GRAAL data qualitatively. However, it is rather difficult to see obvious peak structures at  $E_{\text{cm}} \simeq 1675$  MeV for the spin-3/2 cases due to the strong interference with  $D_{15}(1675)$ . This observation tells us that the new resonance may be identified as a member of the baryon antidecuplet apart from its parity, though there is still a possibility to explain it as one of coupled-channel effects near the  $K\Sigma$  and  $K\Lambda$  thresholds.

## II. GENERAL FORMALISM

In this Section, we set up a theoretical formalism for the investigation of the  $N^*$  resonance in  $\eta$  photoproduction. The effective Lagrangians for each vertex for the backgrounds can be written as follows:

$$\begin{aligned}
\mathcal{L}_{\gamma NN} &= -e_N \bar{N} \gamma_\mu N A^\mu + \frac{ie_Q \kappa_N}{4M_N} \bar{N} \sigma_{\mu\nu} N F^{\mu\nu} + \text{h.c.}, \\
\mathcal{L}_{\eta NN} &= -ig_{\eta NN} \bar{N} \gamma_5 \eta N + \text{h.c.}, \\
\mathcal{L}_{V NN} &= -g_{V NN}^v \bar{N} \gamma_\mu N V^\mu + \frac{ig_{V NN}^t}{4M_N} \bar{N} \sigma_{\mu\nu} V^{\mu\nu} N + \text{h.c.}, \\
\mathcal{L}_{\gamma \eta V} &= \frac{e_Q g_{\gamma \eta V}}{4M_\eta} \epsilon_{\mu\nu\sigma\rho} F^{\mu\nu} V^{\sigma\rho} \eta + \text{h.c.},
\end{aligned} \tag{1}$$

where  $\gamma$ ,  $N$ ,  $\eta$  and  $V$  stand for the fields of the photon, nucleon,  $\eta$  meson and vector mesons ( $\rho$  and  $\omega$ ), respectively.  $e_N$  and  $\kappa_N$  denote the electric charge and anomalous magnetic moment of the nucleon, respectively, while  $e_Q$  the unit charge. Generically, the  $M_h$  denotes the mass of the hadron  $h$ . The strength of the meson-baryon coupling constants are employed

from the Nijmegen potential [11] and given in our previous work [14]. In the following, we present the effective Lagrangians for the resonant contributions of spin 1/2, 3/2 and 5/2:

$$\begin{aligned}
\mathcal{L}_{\gamma NN^*}^{1/2} &= \frac{\mu_{\gamma NN^*}}{2(M_N + M_{N^*})} \bar{N}^* \Gamma_5^a \sigma_{\mu\nu} F^{\mu\nu} N, \\
\mathcal{L}_{\eta NN^*}^{1/2} &= -ig_{\eta NN^*} \bar{N} \Gamma_5^a \gamma_5 \eta N^*, \\
\mathcal{L}_{\eta NN^*}^{3/2} &= \frac{g_{\eta NN^*}}{M_\eta} \bar{N}^{*\mu} \Theta_{\mu\nu}(A, B) \Gamma_5^a N, \partial^\nu \eta \\
\mathcal{L}_{\gamma NN^*}^{3/2} &= \frac{i\mu_{\gamma NN^*}}{M_{N^*}} \bar{N}^{*\mu} \Theta_{\mu\nu}(C, D) \Gamma_5^b \gamma_\lambda N F^{\lambda\nu}, \\
\mathcal{L}_{\eta NN^*}^{5/2} &= \frac{g_{\eta NN^*}}{m_\eta^2} \bar{N}^{*\mu\nu} \Theta_{\mu\delta}(A, B) \Theta_{\nu\lambda}(C, D) \Gamma_5^b N \partial^\delta \partial^\lambda \eta, \\
\mathcal{L}_{\gamma NN^*}^{5/2} &= \frac{\mu_{\gamma NN^*}}{M_{N^*}^2} \bar{N}^{*\mu\alpha} \Theta_{\mu\nu}(E, F) \gamma_\lambda \Gamma_5^a (\partial_\alpha F^{\lambda\nu}) N,
\end{aligned} \tag{2}$$

where the spinors for spin-3/2 and spin-5/2 fermions are defined by the Rarita-Schwinger formalism [12, 13]. For convenience, we turn off the off-shell factor in  $\Theta_{\mu\nu}(A, B)$ , since its effects are rather small. Being similar to the background contributions, the strong couplings can be determined by two-body decay process with the Yukawa interactions given in Eq. (2). Physical inputs (full decay width and branching ratio for each resonance) are also given in Ref. [14]. We note that the values of the physical inputs are compatible with those given by the PDG [15]. The transition photon couplings ( $\mu_{\gamma NN^*}$ ) can be computed via their helicity amplitudes [12]. The invariant amplitudes for each contribution can be evaluated straightforwardly by using Eqs. (1) and (2) as shown in Ref. [14].

### III. NUMERICAL RESULTS

We now show the numerical results for differential cross sections with respect to the center of mass energy ( $E_{\text{cm}}$ ) in Figure 1 for the neutron (upper panels) and proton (lower panels) targets. All curves are drawn at  $\theta_{\gamma\eta} = 140^\circ$ , which is the angle between the incident photon and outgoing  $\eta$  meson. The spin and parity of  $N^*(1675)$  are assigned as  $1/2^+$ ,  $1/2^-$ ,  $3/2^+$  and  $3/2^-$  from the left to the right. We plot the results for different strengths of the transition photon couplings,  $\mu_{\gamma NN^*(1675)}$ . As for the neutron target, we can reproduce the data qualitatively well as shown in the upper panel of Figure 1. In the vicinity of the threshold, the  $S_{11}(1535)$  contribution dominates. The numerical results are underestimated for the region beyond  $E_{\text{cm}} \sim 1.8$  GeV due to the destructive interference between  $S_{11}(1535)$  and the vector mesons, and to the weak  $D_{15}(1675)$  contribution ( $\Gamma_{D_{15}(1675)}/\Gamma_{D_{15}(1675) \rightarrow \eta N} \simeq 1\%$ ) which is similar to those in the model (ii) of Ref. [3]. We observe sharp peak structures at  $E_{\text{cm}} \sim 1.675$  GeV for  $J^P = 1/2^\pm$ . Comparing them to the experimental data taken from the GRAAL experiment [1, 2], we estimate the transition magnetic moment for the  $n^* \rightarrow n\gamma$  decay:  $|\mu_{\gamma nn^*(1675, 1/2^\pm)}| = 0.1 \sim 0.2$  for the spin 1/2 case. On the contrary to the spin-1/2 cases, it is rather difficult to find obvious peak structures for the spin-3/2 case for both parities, because of the strong destructive interference with  $D_{15}(1675)$ . Note that the strength of the  $\mu_{\gamma nn^*(1675, 3/2^\pm)}$  turns out to be around ten times as small as those of the spin-1/2 case. The reason for this smallness lies in the fact that the higher partial-wave contributions come into play in the case of the spin-3/2  $N^*$ . Now we are in a position to discuss the results of the proton target shown in the lower panel of Figure 1. The value of  $|\mu_{\gamma pp^*(1675)}|$

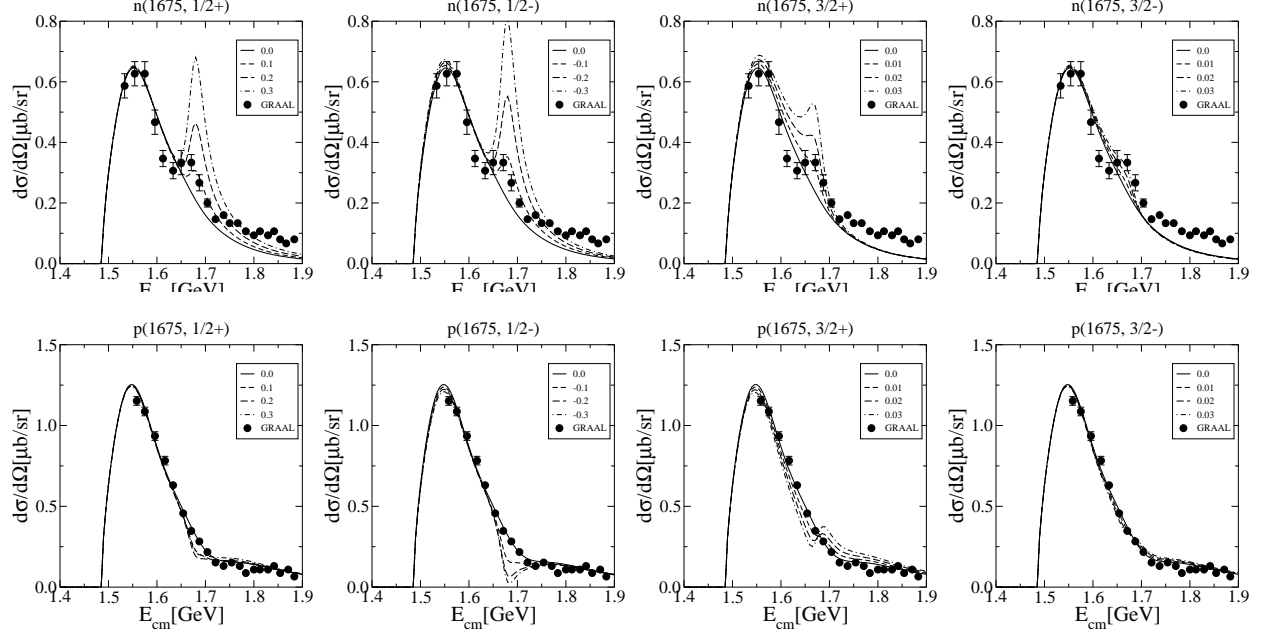


FIG. 1: Differential cross sections for  $\eta$  photoproduction at  $\theta_{\gamma\eta} = 140^\circ$  for the neutron (upper panels) and proton (lower panels) targets. Spin and parity of  $N^*(1675)$  are assigned by  $1/2^+$ ,  $1/2^-$ ,  $3/2^+$  and  $3/2^-$  from the left to the right. Experimental data are taken from Ref. [1, 2].

should be nearly zero to produce the experimental curves for all spin and parity states. In contrast to the neutron target, we can produce the data relatively well for the regions above  $\sim 1.8$  GeV due to the constructive interference between  $S_{11}(1535)$  and the vector mesons. From the numerical results for the differential cross sections, we observe that the new resonance has strong isospin asymmetry by employing the transition photon couplings:  $|\mu_{\gamma nn^*(1675)}| = 0.1 \sim 0.2$  and  $|\mu_{\gamma pp^*(1675)}| \simeq 0$  for the spin-1/2 case as discussed already in the previous work [10]. However, it turns out that no clear peak structure is shown for the spin-3/2  $N^*$ . We emphasize that all of these results support the prediction for  $|\mu_{\gamma NN^*(1675)}|$  from the  $\chi$ QSM [7] in which this new resonance  $N^*$  is treated as a non-strangeness member of the baryon antidecuplet. From the results discussed above, however, we are not able to determine the parity of the resonance within the present theoretical framework, since the results for the  $1/2^-$   $N^*$  are also compatible with the data. It is worthwhile to mention that the  $J^P = 1/2^-$  baryon state can not be achieved by the conventional collective quantization of the soliton in the  $\chi$ QSM. We now present the numerical results for the beam asymmetries as a function of  $E_{\text{cm}}$ , which plays an essential role in determining the new resonance [1, 2]. First, we define the beam asymmetry as follows [1, 2]:

$$\Sigma = \left[ \frac{d\sigma}{d\Omega_{\parallel}} - \frac{d\sigma}{d\Omega_{\perp}} \right] \times \left[ \frac{d\sigma}{d\Omega_{\parallel}} + \frac{d\sigma}{d\Omega_{\perp}} \right]^{-1}, \quad (3)$$

where the subscript  $\parallel$  denotes the polarization vector of the incident photon parallel to the reaction plane, and  $\perp$  for the longitudinally polarized photon. Figure 2 depicts the numerical results for the beam asymmetries as in the same way as Fig. 1. First, we discuss the neutron case as shown in the upper panel of Fig. 2. The results reproduce relatively well the data except for the region below  $\sim 1.6$  GeV due to the strong magnetic  $\omega$ -meson contribution. Note that the  $\Sigma$  has a valley structure around  $E_{\text{cm}} \sim 1.675$  GeV for the spin-1/2 cases

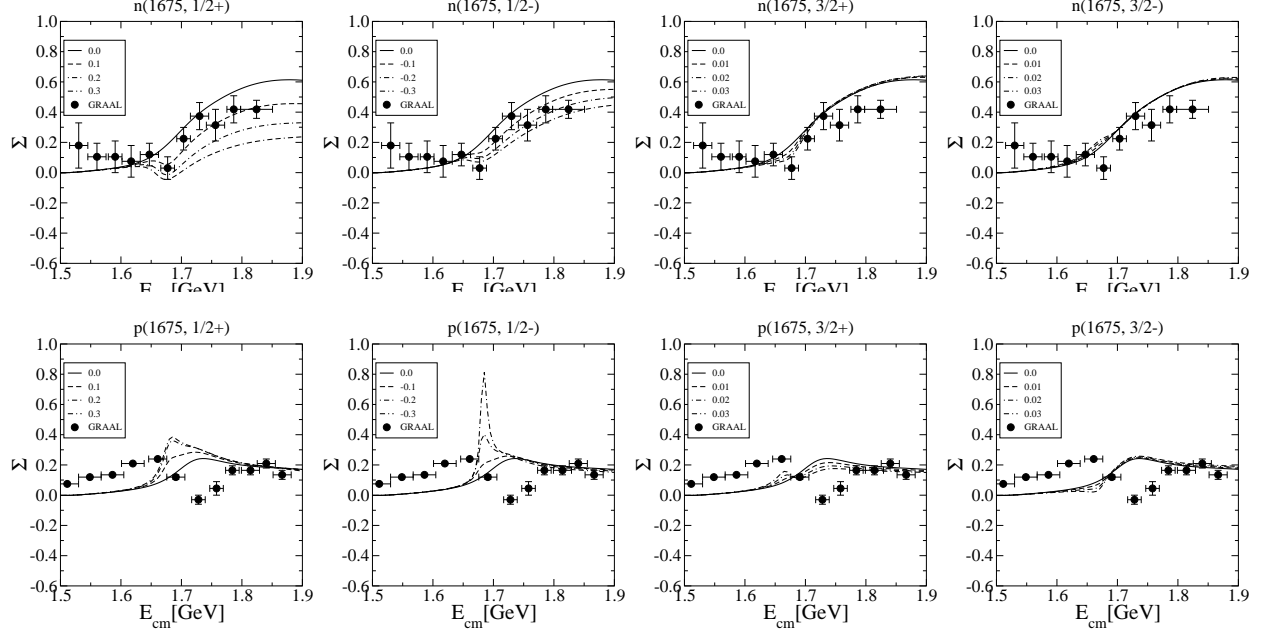


FIG. 2: Beam asymmetries for  $\eta$  photoproduction for the neutron (upper row) and proton (lower row) targets at  $\theta_{\gamma\eta} = 140^\circ$ . Spin and parity of  $N^*(1675)$  are assigned by  $1/2^+$ ,  $1/2^-$ ,  $3/2^+$  and  $3/2^-$  from the left to the right. Experimental data are taken from Ref. [1, 2].

as the value of  $|\mu_{\gamma nn^*(1675)}|$  increases. As argued in Refs. [1, 2], this tendency can be an indication of the new resonance contribution. Although we still have some visible structures for the spin-3/2 cases around  $E_{\text{cm}} \sim 1.675$  GeV, they look much weaker than those for the spin-1/2 cases. In contrast to the neutron case, as seen in the lower panel of Figure 2, we fail to reproduce the data for all spin and parity states, although order of magnitude is rather compatible. Especially, the downward hump and valley structures in the range of  $1.7 \text{ GeV} \leq E_{\text{cm}} \leq 1.8 \text{ GeV}$  in the experimental data are not generated at all. As the strength of  $\mu_{\gamma pp^*}$  increases, we observe clear kinks around  $E_{\text{cm}} = 1.7$  GeV for the spin-1/2 cases due to the interference between the new resonance and  $D_{15}(1675)$ .

#### IV. SUMMARY AND CONCLUSION

In the present talk, we have shown the recent results for the  $\eta$  photoproduction off the nucleon with the effective Lagrangian approach in the Born approximation. We focussed on the new nucleon resonance around  $E_{\text{cm}} \sim 1.675$  GeV, examining its possible spin and parity theoretically and considering  $1/2^\pm$  as well as  $3/2^\pm$ . First, we observed fine peak structures for the new resonance in the differential cross sections being compatible with the GRAAL data, when its spin and parity were assigned to be  $J^P = 1/2^\pm$ . We obtained  $|\mu_{\gamma nn^*(1675,1/2^\pm)}| = 0.1 \sim 0.2$  whereas  $|\mu_{\gamma pp^*(1675,1/2^\pm)}|$  should be almost zero to meet the data. In contrast, there were no clear peaks shown for both  $3/2^\pm$  due to the strongly destructive interference with  $D_{15}(1675)$  within the present theoretical framework. From these observations, the new resonance may be considered as  $N^*(1675,1/2^\pm)$  in the present work. If this is the case, the resonance may possibly be identified as a non-strangeness member of the baryon antidecuplet with  $J^P = 1/2^+$ . In addition, this can be a natural consequence of the  $U$ -spin

symmetry in the  $SU(3)$  baryon representations. Though the present work favors the new nucleon resonance  $N^*(1675)$  as a member of the baryon antidecuplet, we have to mention that it is necessary to consider a possibility that it might arise from the coupled-channel effects near the  $K\Sigma$  and  $K\Lambda$  thresholds.

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